

Combined radiolarian-ammonite stratigraphy for the Late Jurassic of the Antarctic Peninsula: implications for radiolarian stratigraphy

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ABSTRACT

New biostratigraphic data from co-occurring radiolarians and ammonites in Upper Jurassic sequences of the Antarctic Peninsula (Byers Peninsula on Livingston Island and Longing Gap, Graham Land), permit a revised and more refined regional stratigraphy. The new data also allow a revision of the chronostratigraphic assignment of some American radiolarian zones established by Pessagno and collaborators: the boundary of Zone 3-4 is assigned to the latest Kimmeridgian, contrasting the former assignment to the early/late Tithonian boundary. The boundary between Subzone 4 beta and 4 alpha is assigned to the early Tithonian, but was usually correlated with the early late Tithonian/late Tithonian boundary. The new chronostratigraphic data from Antarctica are used together with recent results of Baumgartner and collaborators to revise the age assignment of the North American Late Jurassic radiolarian zones.

KEY WORDS

Radiolaria,
ammonites,
Late Jurassic,
Kimmeridgian,
Tithonian,
biostratigraphy,
Antarctic Peninsula.

RÉSUMÉ

Stratigraphie combinée de radiolaires et ammonites du Jurassique supérieur de la péninsule Antarctique : implications pour la stratigraphie des radiolaires.

De nouvelles données biostratigraphiques obtenues à partir de co-occurrences de radiolaires et ammonites dans les séries du Jurassique supérieur de la péninsule Antarctique (péninsule Byers sur l'île de Livingston et de Longing Gap, Graham Land), permettent de réviser et affiner une stratigraphie régionale. Les nouvelles données permettent aussi une révision des attributions chronostratigraphiques de quelques zonations de radiolaires américaines établies par Pessagno et ses collaborateurs : la limite de la zone 3-4 est assignée au Kimméridgien le plus tardif, contrastant ainsi avec la précédente assignation à la limite Tithonien précoce-tardif. La limite entre la sous-zone 4 beta et 4 alpha est assignée au Tithonien inférieur mais fut habituellement corrélée avec la limite entre les parties inférieure et supérieure du Tithonien supérieur. Les nouvelles données chronostratigraphiques de l'Antarctique sont utilisées en même temps que les résultats récents de Baumgartner et ses collaborateurs pour réviser les attributions d'âge des zones à radiolaires du Jurassique supérieur d'Amérique du Nord.

MOTS CLÉS

Radiolaires,
Ammonites,
Jurassique supérieur,
Kimméridgien,
Tithonien,
biostratigraphie,
péninsule Antarctique.

INTRODUCTION

Although Upper Jurassic sequences with co-occurring radiolarians and ammonites were continuously reported in the last few years (e.g. Pessagno *et al.* 1987a, b; O'Dogherty *et al.* 1989, 1995; Pujana 1989, 1991, 1996; Baumgartner *et al.* 1995b; Zügel 1997), such findings can still be regarded exceptional. Hence, new sections yielding both radiolarian and ammonite faunas are of high value for the improvement of biostratigraphy.

Late Jurassic mudstone sequences of the Antarctic Peninsula contain relatively well-preserved ammonites and radiolarians at several localities. Two sections are described in this paper. The sections belong to the Anchorage Formation (Byers Peninsula, Livingston Island) and Ameghino (= Nordenskjöld) Formation (Longing Gap, Graham Land), respectively. Stratigraphically important macrofossils (ammonites, aptychi, belemnites, bivalves) as well as microfossils (radiolarians) were found in the same sections and sometimes even in the same samples.

The ammonite fauna in the sequences is mainly composed of cosmopolitan or Tethyan elements

showing no significant differences from Tethyan or other eastern Pacific sites on a genus level. Hence, ammonites allow a fairly straightforward chronostratigraphic assignment.

The excellently preserved radiolarian faunas recovered from carbonate concretions exhibit a pronounced Austral aspect (Kiessling & Scasso 1996). Nevertheless, they can be linked to the North American standard zonation (Pessagno *et al.* 1993, 1994) and allow a detailed biostratigraphic subdivision. However, the chronostratigraphic radiolarian ages are always in slight disagreement with ammonite ages.

In this paper we provide a revised chronostratigraphic assignment of the Kimmeridgian/Tithonian North American radiolarian zones established by Pessagno *et al.* (1984, 1987b, 1993) and evaluate the applicability of other radiolarian zonations in Antarctica.

GEOLOGICAL SETTING

The Antarctic Peninsula formed a separate plate which was situated in southern high latitudes during Late Jurassic time (see review in Kiessling & Scasso 1996).

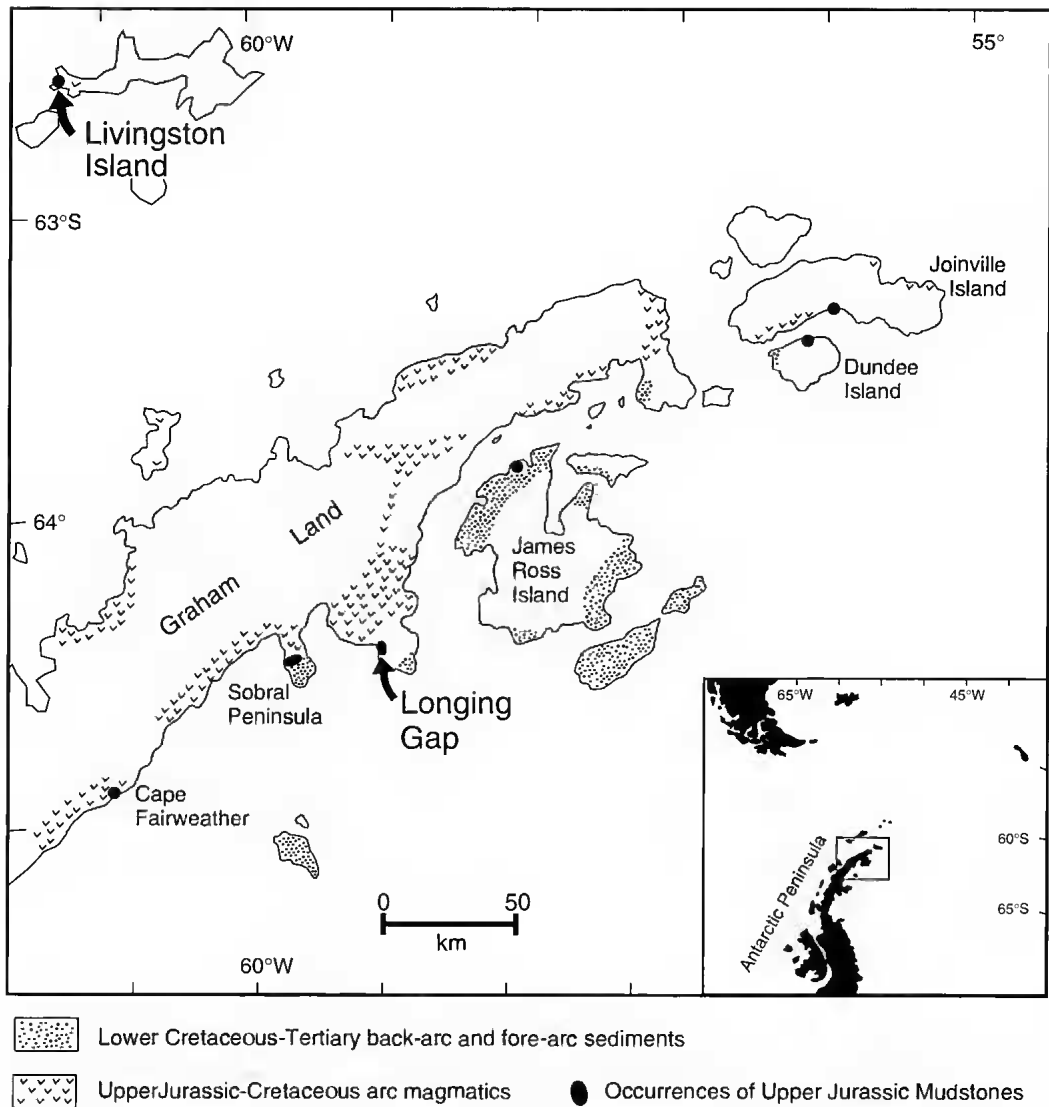


FIG. 1. — Geological map of the northeastern Antarctic Peninsula (Graham Land). The studied localities are printed in bold.

This region is characterized by an almost continuous magmatic activity from the Early Jurassic to the Miocene (Barker *et al.* 1991; Leat & Searrow 1994), similar to the southernmost Andes. During the Jurassic period, the eastward subduction of the Pacific Phoenix Plate led to the development of a calc-alkaline magmatic arc (Antarctic Peninsula Volcanic Group) with volcanoclastic sequences in the fore-arc and back-arc areas. The magmatic arc is thought to have for-

med partly on pre-existing continental crust (Hervé *et al.* 1996).

Back-arc of the Antarctic Peninsula volcanoclastic sediments and anoxic radiolarian-rich mudstones are supposed to unconformably overlay an older accretionary complex, the Trinity Peninsula Group. The mudstone sequence belongs to the mainly Upper Jurassic Ameghino Formation (Medina & Ramos 1981; Medina *et al.* 1983) also known as Nordenskjöld Formation

(Farquharson 1982, 1983) which forms the basal sedimentary infill of the Larsen Basin in the northeastern Antarctic Peninsula (Macdonald *et al.* 1988). The basin contains approximately 6000 m of epi- and volcanoclastic sediments deposited from the Late Jurassic to the Paleogene. Outcrops of the Ameghino Formation are scattered along the eastern coast of Graham Land (Fig. 1). They are either isolated by surrounding ice-masses or found in complex tectonic contact to other rocks.

The Late Jurassic Anchorage Formation is the chronostratigraphic equivalent of the Ameghino Formation in the fore-arc region (Pirrie & Crame 1995). As in the Ameghino Formation mudstones and tuffs prevail, but additional sandstone beds are intercalated. The Anchorage Formation forms the base of a 1000 m thick sequence (Byers Group) ranging from the Kimmeridgian to the Valanginian (Crame *et al.* 1993). The Anchorage Formation is only exposed on Byers Peninsula, Livingston Island.

LOCALITY DESCRIPTIONS

LONGING GAP

Longing Gap is situated at the Nordenskjöld Coast (Larsen Inlet) of northern Graham Land (Fig. 1). The area without permanent ice cover extends some 4 km in a north-south direction and a maximum of 1.5 km in an east-west direction (Fig. 2) and is surrounded by glaciers. Longing Gap is the type locality of the Ameghino Formation and only rocks assigned to the Ameghino Formation are exposed there. The geological structure is a wide syncline with a nearly east-west oriented axis. Beds dip to the south at the northern margin of the exposure; they lie horizontal in the southern part, and dip gently to the north at the southernmost margin. Minor faults are present, but no significant offset was noticed.

The sedimentary succession consists of black mudstones and gray tuffs. Both lithologies are tightly intercalated or mixed. Additionally, calcite concretions are common throughout the section reaching 3 m in diameter. They occur in mudstones as well as in tuffs, but mudstone

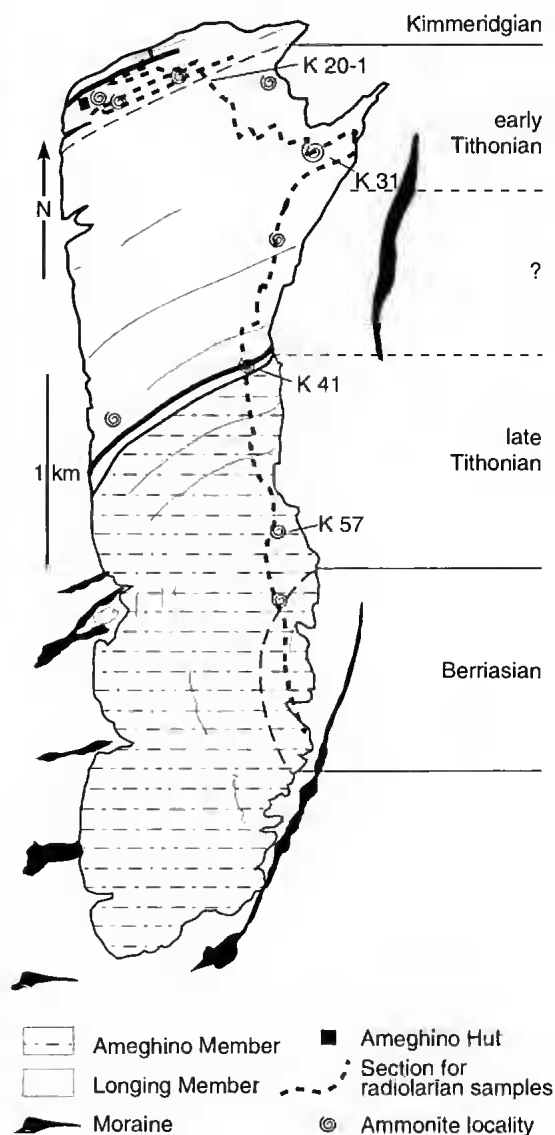


Fig. 2. — Outcrop of the Ameghino Formation at Longing Gap. The profile line for radiolarian samples, important concretion levels and ammonite locations, and the ages provided by ammonites are indicated.

concretions are generally larger. At the base of the succession mudstones predominate, while towards the top tuff beds become increasingly abundant. This trend led Whitham & Doyle (1989) to distinguish two members: a lower Longing Member and a higher "Ameghino" Member. Although there is a continuous transi-

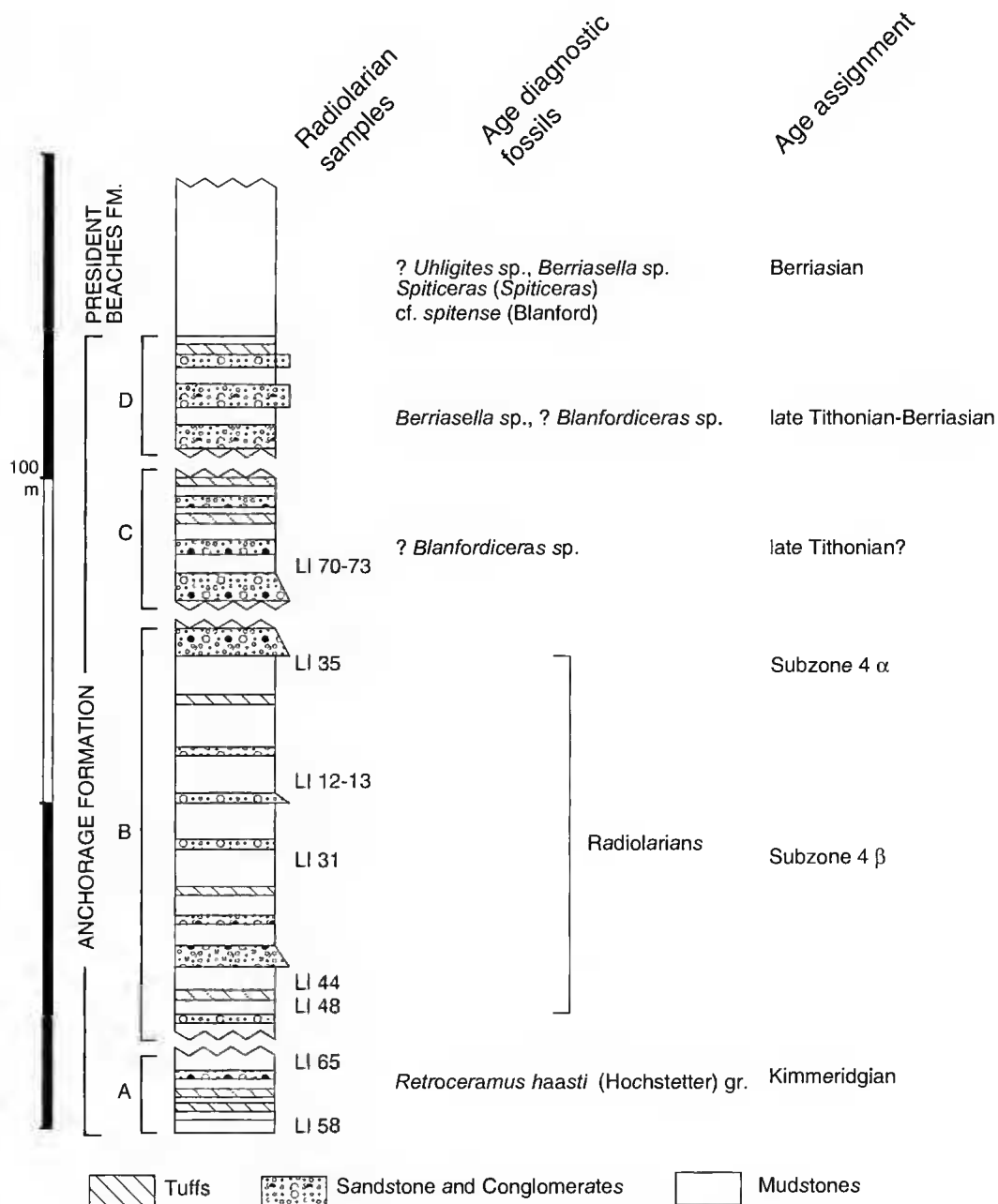


FIG. 4. — Idealized composite section of the Anchorage Formation on Byers Peninsula (Livingston Island). Only radiolarians from Zone 4 could be recovered. Macrofossil ages are based on fauna collected by Crame *et al.* (1993) at the base and own data for the higher part of the section. The late Tithonian age for the upper part of the Anchorage Formation is based on new findings of *Blanfordiceras* sp. and *Berriasella* sp.

quent destruction of lamination indicate dysaerobic conditions.

The Longing Member is more poorly exposed

than the "Ameghino" Member. Only about one fourth of the Longing Member is exposed in place, whereas more than half of the "Ameghino"

Member is well exposed. However, with the exception of some small displacements due to cryoturbation, most of the loose blocks forming the scree cover can be considered in place. This is indicated by weathered carbonate concretions that are perfectly traced in the scree. Therefore, it was possible to get a complete section of the Ameghino Formation at Longing Gap.

The sequence contains common macrofossils (ammonites, belemnites, bivalves, aptychi, fishes, driftwood) allowing a stratigraphic subdivision. We emphasize on ammonites in this paper. Although the microfauna is diverse as well (radiolarians, sponge spicules, foraminifera, paly-nomorphs), we exclusively refer to radiolarians herein. The ammonites, like most other macrofossils, are particularly enriched in certain horizons, which are often widely separated. Radiolarians are only well preserved in carbonate concretions. However, the concretions are continuously distributed in the Longing Gap Section. As a consequence the radiolarian documentation is more continuous than the ammonite documentation.

BYERS PENINSULA

The Anchorage Formation was defined by Crame *et al.* (1993). It is composed of dark gray to black mudstones interbedded with sandstones and tuffs. Its true boundaries have not been observed. Although it is separated from the overlying Betriasiian President Beaches Formation by a fault, facies analysis indicates a transitional change between this two units.

Detailed mapping (Lopetrone 1997) allowed the recognition of several Anchorage Formation outcrops in fault-bounded blocks showing different facies associations. Crame *et al.* (1993) suggested a minimum thickness of the composite section of 105 m. A composite section quite different and difficult to match with the one of Crame *et al.* (1993) resulted from our work (Fig. 4), probably as a consequence of the structural complexity of the area. The integrated thickness of the Anchorage Formation is close to 120 m including an uppermost sequence transitional to the President Beaches Formation.

The whole sequence is composed of radiolarian-rich mudstones with intercalations of tuffs and –

in contrast to the Ameghino Formation – sandstone beds (see Pirrie & Crame 1995, for a detailed description). The sandstone beds reach up to 80 cm in thickness and show evidence of turbiditic sedimentation. Carbonate concretions occur throughout the section. However, they are smaller than at Longing Gap and many are silicified. As in the Ameghino Formation there is a shift from parallel-laminated to intensely bioturbated mudstones within the sequence.

Our composite section is composed of four intervals. The lowermost exposure is about 11 m thick. It is separated from the middle part by a fault with uncertain offset. This middle part is about 55 m thick. A one meter thick conglomerate occurs at the top of this part of the section. The upper two parts of the section reach a composite thickness of around 50 m and are predominated by sandstones and conglomerates.

In contrast to Longing Gap, age diagnostic macrofossils are relatively rare on Byers Peninsula. Driftwood, bivalves, belemnites, and a few ammonites could be recovered. The carbonate concretions bear very well preserved radiolarian faunas in the middle section.

FAUNAL CHARACTERISTICS

Owing to the high paleolatitude of the Antarctic Peninsula the fossils are expected to show biogeographical differences as compared with lower paleolatitude sites. Since paleobiogeography has some impact on stratigraphic correlation we shortly discuss biogeographical affinities of both ammonites and radiolarians below.

Ammonites are affected by the high latitude depositional environment by their reduced diversity and some morphological modifications. With the probable exception of *Blanfordiceras*, all Antarctic genera are to be found in Tethyan sections as well. There is no striking evidence for an Austral ammonite province in the Tithonian which could be equivalent to the Northern Hemisphere Boreal provinces (Callomon in Hillebrandt *et al.* 1992, but see also Enay & Cariou 1997).

In contrast, the radiolarians display a pronounced Austral aspect, both in the Ameghino

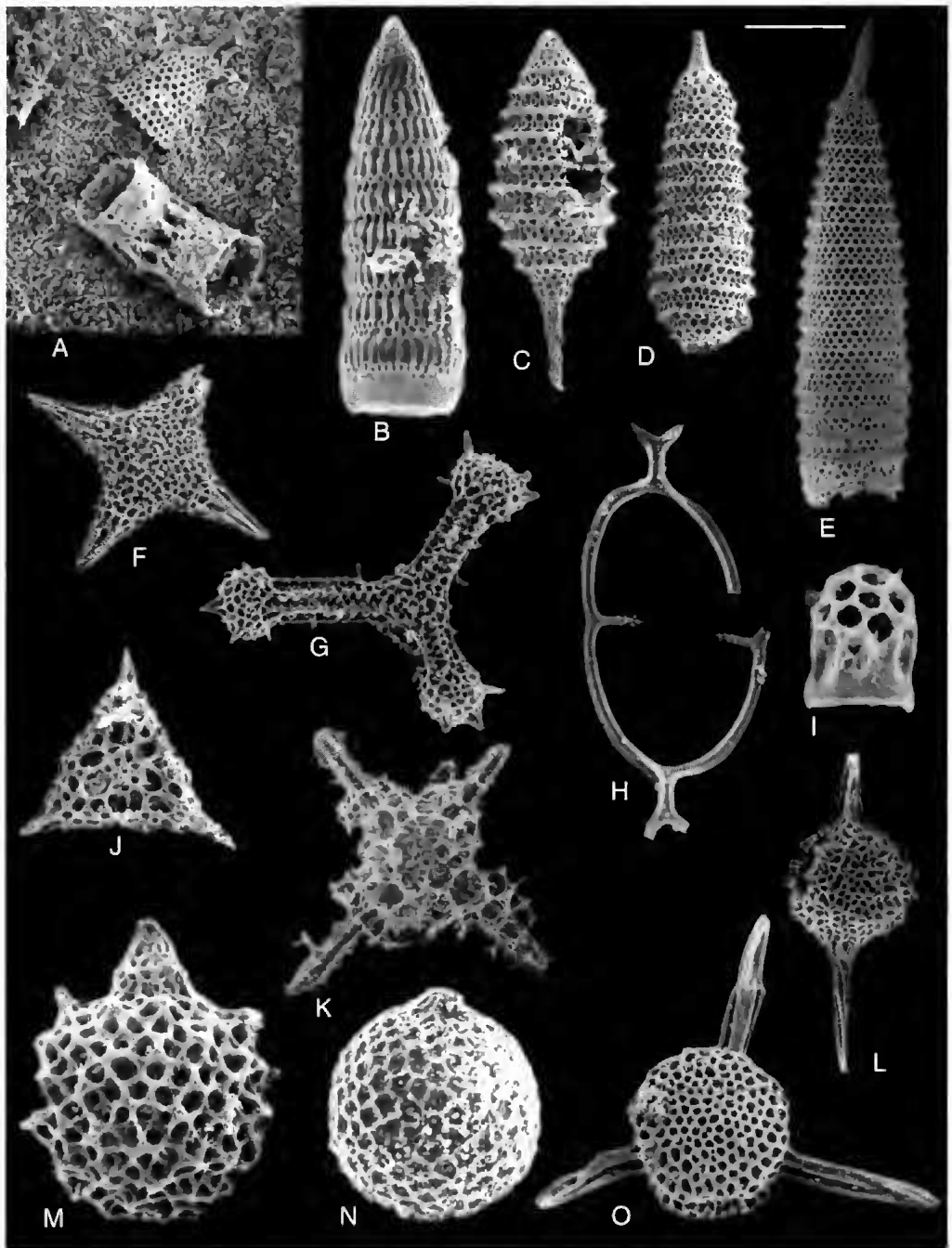


FIG. 5. — Age diagnostic radiolarians from Byers Peninsula (LI) and Longing Gap (K, LG). A, *Bivallupus mexicanus* Pessagno & MacLeod, etched concretion cut parallel to bedding (K 20-1); B, *Loopus primitivus* (Matsuoka & Yao) (LI 31); C, *Tethysetta boesii* gr. (Parona) (K 44); D, *Parvicingula colemani* Pessagno & Blome (K 25); E, *Parvicingula excelsa* Pessagno & Blome (LG 1); F, *Crucella theokattensis* Baumgartner (K 14-1); G, *Tribrabs rhododactylus* Baumgartner (LI 31); H, *Acanthocircus furiosus* Jud (LI 31); I, *Vallupus hopsoni* Pessagno & Blome s.l., very small specimen (LI 44); J, *Perispyridium ordinarium* (Pessagno) gr. (K 6); K, *Haliodictya* (?) *antiqua* (Rüst) s.l. (K 14-1); L, *Acaeniotyle parva* Yang = *Acaeniotyle umbilicata* (Rüst) gr. (K 13); M, *Sethocapsa trachyostraca* Foreman (K 13); N, *Gongylothorax favosus* Dumitrica (K 4); O, *Suna echiodes* (Foreman) s.l. (LI 13). See Kiessling (1999) for figures of additional age diagnostic radiolarians. Scale bar: A, 76 µm; B, I, M, N, 50 µm; C-H, J-L, O, 100 µm.

Formation and in the Anchorage Formation. The faunas exhibit typical high latitude characteristics as indicated by the predominance of *Parvicingula/Praeparvicingula* (Fig. 5D, E). The Antarctic faunas are especially similar to the Southern Boreal Province as defined by Pessagno & Blome (1986), Pessagno *et al.* (1993), and Hull (1997). Both the Austral Province and the Southern Boreal Province have many species in common and share features such as the fluctuating pantanelliid abundance and the high diversity of *Parvicingula* (Hull 1995; Kiessling 1999).

Compared with faunas from equivalent latitudes on the Northern Hemisphere, Pantanelliidae are considerably more abundant (Kiessling & Scasso 1996). Typical Tethyan taxa such as *Tritrabs* and *Podocapsa* are rare but present. *Vallupus hopsoni* and other vallupins are present, which is very useful for stratigraphic correlation. *Hsuum* and *Perispyridium* are as common as in Tethyan sections and can also be used for global correlations. However, the stratigraphically important Tethyan taxa *Mirifusus*, *Ristola*, and *Acanthocircus dicranacanthos* (Squinabol) are totally absent in Antarctica which limits the correlation with Tethyan sections.

A selection of stratigraphically important radiolarians is shown in Figure 5. A more comprehensive taxonomic framework is provided by Kiessling (1999).

STRATIGRAPHY

Former ammonite and bivalve data suggested an age range of Kimmeridgian/early Tithonian to late Tithonian/Berriasian for the investigated sections (Whitham & Doyle 1989; Crame *et al.* 1993; Pirrie & Crame 1995). Our new material is essentially in agreement with previous designations, but we are now able to provide a more detailed stratigraphic subdivision.

The first stratigraphic subdivision of the Longing Gap Section based on radiolarians was proposed by Kiessling & Scasso (1996) and Kiessling (1996). Referring to the North American standard zonation the authors came to the conclusion that the age range of the Ameghino Formation is early Tithonian to Berriasian. Our

new material shows that although the radiolarian zonation of the sequence is still valid, the chronostratigraphic calibration needs to be revised.

The discussion of ammonite ages relies on comparisons with Antarctic, Argentinean, European, and Himalayan zonations, whereas the radiolarian zones are first exclusively compared with the North American zonation of Pessagno *et al.* (1984, 1987, 1993, 1994) and Hull (1997).

STRATIGRAPHY OF LONGING GAP

Ammonites (A. Zeiss and A. C. Riccardi)

The first ammonite from Longing Gap, a Late Jurassic *Perisphinctes* sp., was mentioned by Bibby (1966). Further investigations were undertaken by Medina & Ramos (1981, 1983), Thomson (1982), Farquharson (1983), Medina *et al.* (1983), Zeiss (manuscript 1985), Whitham & Doyle (1989), and Doyle & Whitham (1991). New material was collected during the Argentinean Antarctic field campaign (1993/1994) by Scasso, Santisteban and Kiessling. Most ammonites are difficult to identify, as incomplete and crushed specimens prevail; often only impressions of crushed ammonites are available. Therefore, many determinations are obtained not with the same security as from better preserved material; this should be kept in mind when using the determinations below.

From base to top we can identify the following macrofossils (horizons are numbered according to the closest concretion level, Fig. 3):

K 16 [LG 11]. *Virgatixioceras* cf. *setatoides* (Berckhemer & Hölder) (Fig. 6F): the impression of a crushed perisphinctid ammonite with relatively coarse ribs. Ribs predominantly bifurcating, but sometimes trifurcating ("polygyrate"). The ribbing style resembles somewhat that of "*Perisphinctes*" *uracensis* (Berckhemer & Hölder, 1959, pl. 7/35), but the ribs are branching a little deeper near the middle of the flanks and the secondaries are somewhat more inclined. Thus, the specimen fits better to a paratype of *Virgatixioceras setatoides* (Berckhemer & Hölder 1959, Fig. 30).

K 16 [LG 4]. *Virgatixioceras* cf. *setatoides* (Berckhemer & Hölder): an impression of a crushed *Virgatixioceras*. The specimen is rather close to *Virgatixioceras setatoides* (Berckhemer &



FIG. 6. — Age diagnostic ammonites from Longing Gap. **A**, ? *Virgatospinectes densistriatus* (Steuer) (LG 20); **B**, *Virgatospinectes* aff. *australis* (Burckhardt) (LG 25); **C**, *Taramelliceras* cf. *prolithographicum* (Fontannes) [LG 16(1)]; **D**, *Aulacosphinctoides* (?) sp. juv. [LG 16(2)]; **E**, *Subplanitoides* cf. *oppeli* Zeiss [LG 9(2)]; **F**, *Virgataxioceras* cf. *setatoides* (Berckhemer & Hölder) (LG 11). Scale bar: 1 cm.

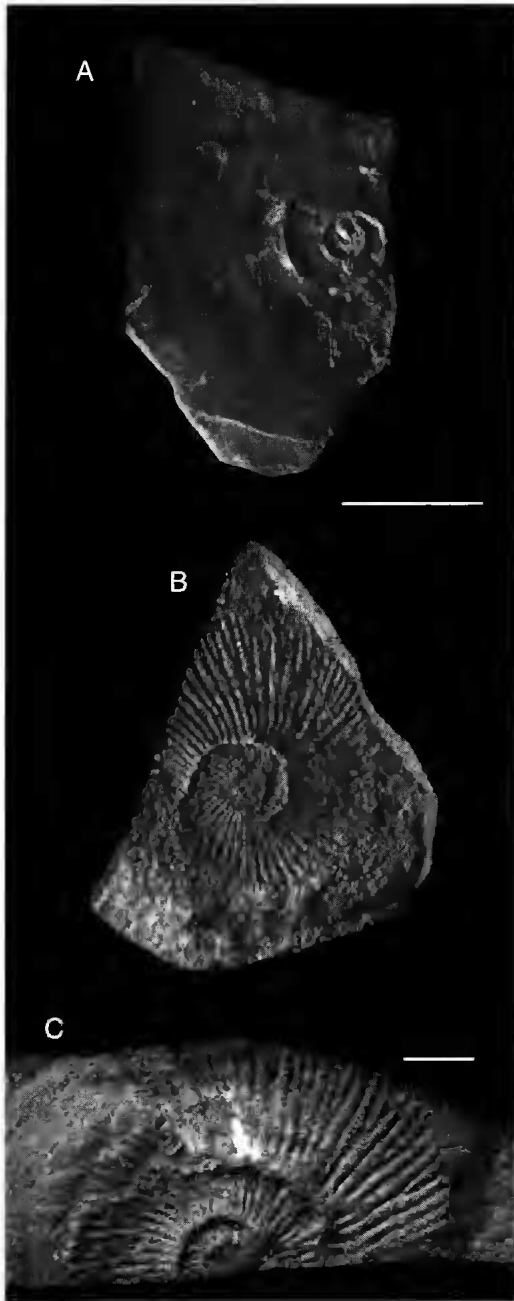


FIG. 7 — Age diagnostic ammonites from Longing Gap. A, *Neochetoceras* (?) sp. (LG 9(1)); B, *Kossmatia* (?) cf. *tenuistriata* (Gray) (LG 3); C, *Virgatospinctes alternecostatus* (Steiger) (LG 29). Scale bars: 1 cm.

Hölder 1959, fig. 31). The shape and the ribbing style agree well. Differences are indicated by the somewhat more rigid recticostate and denser rib-

bing as well as by the branching point of the ribs situated a little deeper on our specimen.

K 16 [LG 6]. ?*Virgatixioceras* cf. *setatoides* (Berckhemer & Hölder): a rather poorly preserved specimen. Considering shape and ribbing style it seems to belong to the above described species or to a related late Kimmeridgian perisphinctid. A similar specimen has been described from the Antalo Limestone of Ethiopia (Jordan 1971).

K 17 [043]. *Glochiceras percevali* (Fontannes); *Glochiceras* cf. *lithographicum* (Oppel); *Taramelliceras* n. sp., aff. *prolithographicum* (Fontannes); *Torquatisphinctes babyensis* Spath; *Lamellaptychus lamellosus* (Parkinson): this sample contains a new species of the *Taramelliceras prolithographicum*/*Glochiceras lithographicum* group. The peculiar ribbing on the flanks of a large specimen is rather similar to *Taramelliceras hemipleura*, while overall morphology, ribs, and nodes of the outermost part of the flanks and the marginal and ventral region are well comparable with stronger ribbed variants of the *T. prolithographicum*/*G. lithographicum* group.

A similar, but smaller species of the same group is *T. flandrini* (Collignon 1960, pl. 147, fig. 583) from the early Tithonian of Madagascar. That species has a wider umbilicus, is stronger ribbed and shows no nodes in the center of the external side.

K 17 [044]. *Katrolliceras* sp., *Retroceramus* cf. *haasti* (Hochstetter).

K 18 [045]. *Torquatisphinctes* sp.

K 18 [LG 16(1)]. *Taramelliceras* cf. *prolithographicum* (Fontannes) (Fig. 6C): an impression of a partly preserved *Taramelliceras*. The outer part of the flanks is well observable. These are ornamented with falcate ribs. The inner part of the ribs is not strongly curved, the outer part is curved forward. The ribs bifurcate occasionally. The ends of the ribs are marked by small tubercles. A row of tubercles is also observed on the venter. The ribbing style is characteristic for *Taramelliceras prolithographicum* (Fontannes). However, as we cannot observe the inner parts of the flanks and the specimen is not complete, we determine it as *Taramelliceras* cf. *prolithographicum*.

There is some affinity to *T. cf. rigidum* as figured

by Medina *et al.* (1983, pl. 2e), but this determination does not agree with the description of the species by Hölder (1955) and his illustration of the holotype.

K 18 [LG 16(2)]. *Aulacosphinctoides* (?) sp. juv. (Fig. 6D): this small specimen is difficult to identify, as young specimens of the genera *Aulacosphinctoides*, *Katrolliceras* and *Torquatisphinctes* can be very similar and only the cross-section could help to distinguish them (cf. Spath 1931). However, there is a rather good correspondence between the shape of our specimen and those of young *Aulacosphinctoides* as figured by Spath (1931, pls 78/4, 79/7). Bearing in mind the problems mentioned above, specimen is best identified as *Aulacosphinctoides* (?) sp. juv.

K 29 [LG 9(1)]. *Neochetoceras* (?) sp. (Fig. 7A): a rather well-preserved fragment of a compressed oppeliid with narrow umbilicus. The poor preservation of the suture does not allow to decide if the specimen belongs to the *Haploceras subelatum* group. As the overall shape is that of *Neochetoceras* (see Oppel 1863, pl. 69/3), this specimen can be assigned to *Neochetoceras* (?) sp.

K 29 [LG 9(2)]. *Subplanitoides* cf. *appeli* Zeiss (Fig. 6E): an impression of a densely ribbed perisphinctid fragment. A cast of the specimen is very close to *Subplanitoides appeli* Zeiss (1968, pl. 8/2). As the venter is not observable a determination as *Subplanitoides* cf. *appeli* is justified.

K 29 [LG 10, LG 27]. *Neochetoceras* (?) sp.: several oppeliid specimens, crushed. Similar forms have been figured by Whitham & Doyle (1989, fig. 6e). They agree in shape with *Neochetoceras*. In order to exclude the possibility that they belong to *Pseudolissoceras*, the poorly preserved remains of suture-lines were closely observed. In the end we are convinced that the sutures suggest an assignment to *Neochetoceras* rather than to *Pseudolissoceras*.

?K 29 [LG 28]. *Glochiceras* sp.: another oppeliid specimen. The wider umbilicus suggests an assignment to *Glochiceras* rather than to *Neochetoceras*.

K 30 [LG 3]. *Kossmatia* (?) cf. *tenuistriata* (Gray) (Fig. 7B): fragment of a small ammonite. The ribbing is rather fine and dense. The branching point is situated in the upper part of the flanks. On the inner part of the last whorl the secondaries are bent forward. At the end of the shell the

specimen is somewhat damaged and the bend is not well preserved. The determination of such a small specimen is difficult, especially when the ventral side can not be inspected. Some affinity exists to similar densely ribbed forms like *Kossmatia* aff. *tenuistriata* Gray (Thomson 1983, fig. 3g) or some *Virgatospinctes* of the *tenuilineatus-burckhardti* group (cf. Indans 1954, pl. 13/1, 4). There is also some resemblance to the inner whorls of a "*Lithacoceras* sp.", as figured by Whitham & Doyle (1989, fig. 6g). Judging from the ribbing on the outer whorl, the form of Whitham & Doyle does not belong to *Lithacoceras*, but more likely to forms like *Franeumites tenuiplicatus* Zeiss (1968, pl. 11/4). *Paraberriassella blondeti* Zeiss (1968, pl. 12/2) is also comparable to our form, but exhibits a different development of ribs on the outer whorl. All these forms come from the upper part of the lower Tithonian. The determination as *Kossmatia* (?) cf. *tenuistriata* is therefore only one of several other possibilities.

K 31 [013, 038a-e, 046, LG 12, LG 14, LG 25, LG 29]. A 1 m thick bank with abundant ammonites: ? *Aulacosphinctoides* sp.; *Haploceras* sp.; Oppeliidae indet.; ? *Taramelliceras* sp.; *Substreblites* or *Ubligites* aff. *krafftii* (Uhlig); *Virgatospinctes* cf. and aff. *andesensis* (Douvillé); *Virgatospinctes* sp.; *Virgatospinctes* (*Lithacoceras*) sp.; *Lamellaptychus* cf. *lamellosus* (Parkinson); *Virgatospinctes alternecostatus* (Steiger); *Virgatospinctes* aff. *australis* (Burckhardt).

[013]. ? *Substreblites* or *Ubligites* aff. *krafftii* (Uhlig): a specimen of 47 mm in diameter, very involute and with fine falcoid ribbing. It looks like the specimens figured by Thomson (1979, pls 2/q, 3/d, f) under the above mentioned names. However, determination is doubtful since the venter could not be observed and the ribbing is stronger.

[LG 29]. *Virgatospinctes alternecostatus* (Steiger) (Fig. 7C): half of the ammonite is preserved. The ribbing style is similar to *V. denseplicatus rotunda* (Spath 1931, pl. 96/2), but the umbilicus is more narrow. In this respect "*Perisphinctes*" *alternecostatus* Steiger (1914, pl. 104/1) fits better. This species seems to belong to *Virgatospinctes* representing an intermediate form between the

denseplicatus and *communis* group.

[LG 25]. *Virgatospinctes* aff. *australis* (Burckhardt) (Fig. 6B): a fragmentary specimen of *Virgatospinctes* with a rather narrow umbilicus, but with more distant, polygyrate and bifurcate ribs (cf. Indans 1954, pl. 20/6).

K 32 [LG 22, K 32]. *Subdichotomoceras* sp.; ? *Virgatospinctes* sp.

K 34 [020, 025, 035, X8]. *Virgatospinctes* ["*Lithacoceras*" Indans] sp.; *Aulacosphinctoides* (?) cf. *patagoniensis* (Favre in Tavera); *Buchia* cf. *hochstetteri* (Fleming); *Buchia* sp.

[025]. *Aulacosphinctoides* (?) cf. *patagoniensis* (Favre in Tavera): a fragment of a rather large perisphinctid. The bifurcation point is changing in height between the inner third and the outer third of the flanks on the penultimate and outer whorl. Ribs on inner whorl split up in half to two thirds of the height of the flanks. There is no virgatotomy or polygyrate splitting of the ribs. Single ribs are intercalated especially on the outer half of the penultimate and on the last whorl.

Since the specimen is fragmentary the assignment to *Aulacosphinctoides* remains questionable. A designation to *Torquatisphinctes* could also be possible. There is some affinity to specimens figured as "*Blanfordiceras patagoniense*" (Favre) Feruglio by Tavera (1970, pl. 3/8). However, those forms are smaller, more coarsely ribbed, and the high outer whorl of our specimen is absent.

K 40-1 [LG 20]. ? *Virgatospinctes densistriatus* (Steuer) (Fig. 6A): an impression of a densely ribbed, virgatospinctid ammonite with a rather narrow umbilicus. It has a good counterpart in the specimen figured by Indans (1954, pl. 21/5) as *V. densistriatus* (Steuer), but there is also a distinct affinity to undescribed forms of *Catutospinctes* Leanza & Zeiss (1992) from Zapala, Argentina.

K 41. ? *Kawhiaspinctes* cf. *antipodus* Stevens: a fragment, broken at about the level of midflanks or slightly above. Only the outer half of the flanks with straight and slightly prosiradiate ribs can be observed. Any probable bifurcation point of the ribs should be situated deeper. The flanks are similar to the outer flanks of *Kawhiaspinctes antipodus* Stevens (1997, pl. 32/3) or *Virgatospinctes* aff. *denseplicatus* (Thomson 1979,

pl. 14/a). However, the latter is more densely ribbed and does not fit well. The specimen is too poorly preserved for any more precise identification.

K 57. *Blanfordiceras* cf. *weaveri* Howlett: a specimen of 87 mm in diameter with an umbilicus of ca. 40 mm. The venter is not preserved; of the last whorl only one quarter is preserved. The ribbing is similar to that in specimens figured from Antarctica as *Blanfordiceras weaveri* by Howlett (1989, pl. 2/5, 7), but our form is more evolute and the ribbing is somewhat coarser. The same is true in comparison with the specimen figured by Krantz (1928, pl. 3/4) or Weaver (1930, pl. 3/356-357). The ribs divide above midflank and are widely spaced in the last quarter of the whorl as in "*Blanfordiceras wallichi*" Gray as figured by Steuer (1891-1892, pl. 16/1). There is also some similarity to *Blanfordiceras delgai* Collignon (1960, pl. 166/680).

[030]. *Substeuroceras* or *Parodontoceras* sp. The specimen is comparable to the one figured by Olivero *et al.* (1980, pl. 1/2) from James Ross Island. It is also similar to *Kassinatia carsensis* (Thomson 1975).

[A1]. *Blanfordiceras* cf. *weaveri* Howlett: this ammonite stems from a moraine deposit above the top of the section. The specimen is comparable with "*Berriassella subprivasensis*" Krantz (in Thomson 1979, pl. 7/i), which was included by Howlett in his new species *B. weaveri*. It is also similar to "*Berriassella behrendseni*" of Feruglio (1936, pl. 7/3-7, 9).

Stratigraphic subdivision based on ammonites

Medina & Ramos (1981) and Medina *et al.* (1983) described ammonites from Longing Gap that can be assigned to the early to middle Kimmeridgian. Our new material did not contain ammonites of this age.

In our section, the first horizons with ammonites occur some 80 m above the base (K 16, K 17). These levels belong to the late Kimmeridgian *Hybonotoceras beckeri* zone. The presence of this substage is also demonstrated by a specimen figured by Whitham & Doyle (1989, fig. 6c) as *Hybonotoceras* sp. This form appears to represent the microconch of a new species of *Hybonotoceras* (*Hybonotella*) which belongs to the group of

H. beckeri. The specimen of Whitham & Doyle can best be compared with the inner whorls of a macroconch figured as "*Hybonoticerus hybonotum*" by Collignon (1960, pl. 132/494) from the "Kimméridgien moyen" of Madagascar. However, the species and age assignment of Collignon cannot be affirmed.

The presence of Submediterranean taxa (*Virgatospirifer*, *Hybonoticerus*) in Antarctica may be astonishing. However, Zeiss (1971, 1979) has shown that these genera are widespread along the eastern part of Africa (Ethiopia-Tanzania). Those forms probably immigrated together with Indian taxa (cf. Howlett 1989) via the Malagassian seaway into the Antarctic Region.

The early Tithonian *Hybonoticerus hybonotum* zone is reached in concretion level K 18 as proved by characteristic *Taramelliceras* species. In the middle part of the Longing Member (K 29, K 30-1) the ammonites may correspond with the *Mucronatum* and *Viminus* zones of Southern Germany. They are comparable with *Subplanitoides*, *Franconites* and to the Pacific genus *Kosmatia*.

Higher in the section, some 70 meters above the former ammonite horizon, we find a typical *Virgatospirifer* fauna similar to that of the Argentinean Neuquén Basin (K 31-K 32). This fauna is assigned to the late early Tithonian *Mendozanus* zone in Argentina.

Virgatospirifer is present up to level K 40-1. It should be noted that true middle Tithonian elements of South America (*Pseudolissoceras* and *Aulacospirifer proximus*) have not been discovered in Longing Gap so far. Reports from other Antarctic localities are very doubtful, too. However, the Antarctic *Virgatospirifer* fauna may also represent the middle Tithonian and reach up even until the earliest late Tithonian. The *Virgatospirifer*-*Hildoglochiceras* assemblage of Spiti was assigned to the middle Tithonian by Krishna *et al.* (1982) and Enay & Cariou (1997) assigned their *Virgatospirifer* assemblage to the late Tithonian. The latter is characterized by *V. denseplicatus* which is also known from Antarctica (Howlett 1989). It is especially remarkable that in the upper part of the *Virgatospirifer* beds of Longing Gap (K 34-K 40) only densely ribbed forms predominate

which do not branch up in more than three secondaries. The specimen of K 41 could be of middle or late Tithonian age (cf. Stevens 1997; Enay & Cariou 1997). We preliminarily assign the beds above K 32 to the earliest late Tithonian *Densiplicatus* zone. Further investigation is necessary to define the range of the *Virgatospirifer* fauna more precisely in the Antarctic region.

The first occurrence of *Blanfordiceras* s.s. is noted in concretion level K 57 providing clear evidence for late Tithonian. On Alexander Island (Howlett 1989) the *Blanfordiceras* fauna includes *Lytobolites weaveri*, a true *Lytobolites*. Species of this genus have been found in Chile (Biro-Bagoczky 1984) in the *Corongoceras alternans* zone, the second zone of the late Tithonian in South America. It corresponds approximately with the zone of *Paraulacospirifer transitorius* in Mediterranean Europe, i.e., the middle part of the late Tithonian. This is in agreement with Thomson (1979) and Howlett (1989) who considered the *Blanfordiceras* zone as part of the late Tithonian.

Some 30 m above K 57 follow beds that can questionably be correlated with the Argentinean *Substeuroceras koeneni* zone. We can suppose the Jurassic/Cretaceous boundary in these beds (cf. Zeiss 1986).

Near the top of the section a Berriasian age is suggested by *Spiticeras* (*Spiticeras*) according to Whitham & Doyle (1989).

North American radiolarian zones at Longing Gap

The base of the Longing Gap Section is assigned to Zone 3 as indicated by the presence of *Caneta bairi* (Pessagno) and the absence of *Vallpus hopsoni* Pessagno & Blome. Since neither *Turanta* s.s. nor *Hsuum maxwelli* Pessagno were found, we presume that the basal part of the Longing Gap Section belongs to upper Subzone 3 alpha, although the primary marker taxon *Napora burckhardti* Pessagno, Whalen & Yeh was not recorded (= exclusively Tethyan marker taxon according to Pessagno *et al.* 1987b). The secondary marker taxa *Parvicingula colemani* Pessagno & Blome (Fig. 5D) and *Hsuum mclaughlini* Pessagno & Blome are present near the base indicating Subzone 4 beta. However, the primary

marker taxon *Vallupus hopsoni* was not recorded, although pantanelliids and even vallupins are common in some samples and we have searched for this species intensely. The last distinct horizon before the evolutionary first appearance of *V. hopsoni* is K 14-1, K 15. Above those samples *V. hopsoni* is absent, but the scarcity of other pantanelliids indicates that its absence may be due to paleoceanographic factors.

The base of Zone 4-Subzone 4 beta is well defined by the first appearance of *Vallupus hopsoni* in sample K 20-1. This is noted just above the first Tithonian ammonites assigned to the *Hybodontum* zone. The first occurrence of *Vallupus hopsoni* provides the most reliable datum in the section. It will be discussed in detail below. Up section *V. hopsoni* is continuously present in samples with a high total pantanelliid abundance. The top of Subzone 4 beta is marked by the last appearance of *Perispyridium* in concretion K 29. *Perispyridium* is represented by two new species within Subzone 4 beta (Kiessling 1999). It is continuously recorded in all better preserved assemblages. The last occurrence of *Perispyridium* is noted between ammonite assemblages assigned to the early Tithonian *Mucronatum* and *Vimineus* zones, respectively.

Marker taxa in Subzone 4 alpha and the suspected Zone 5 are rare. The base of Subzone 4 alpha is characterized by abundant Pantanelliidae including *Vallupus hopsoni* and the absence of *Perispyridium*. The last occurrence of *V. hopsoni* is noted some 20 m above the ammonite horizon that has been assigned to the late early Tithonian *Mucronatum* zone. The upper boundary of Subzone 4 alpha is poorly defined owing to the absence of primary marker taxa. It is preliminarily drawn between the last occurrence of *Parvicingula colemani* Pessagno & Blome and the first occurrence of *Williriedellum ruesti* (Tan Sin Hok). The radiolarian ages are without major contradictions with regard to the zonation of Pessagno *et al.* (1993). However, the secondary and corporeal marker taxa *Parvicingula colemani*, *Parvicingula jonesi* Pessagno s.l. and *Hsuum mclaughlini* s.l. occur slightly earlier than predicted in Pessagno's zonation.

In summary, the Ameghino Formation at Longing Gap ranges from the Kimmeridgian to the early Berriasian. The Longing Member ranges from the Kimmeridgian to probably the earliest late Tithonian and the "Ameghino" Member is assigned to the late Tithonian to early Berriasian. The part of radiolarian Zone 3 exposed at Longing Gap (top of Subzone 3 alpha) can be assigned to the Kimmeridgian. The base of Zone 4 is likely to coincide with the base of the Tithonian or latest Kimmeridgian. The boundary between Subzone 4 beta and Subzone 4 alpha is assigned to the middle part of the early Tithonian (*sensu* Gallico). The boundary between Zone 4 and Zone 5 is less clearly defined at Longing Gap. The occurrence of *Spiticeras* (*Spiticeras*) approximately coincides with radiolarian assemblages preliminarily assigned to Zone 5. This would indicate that the boundary of Zone 4-Zone 5 agrees with the Jurassic-Cretaceous boundary. A more detailed discussion follows below.

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STRATIGRAPHIC SUMMARY OF BYERS PENINSULA

Radiolarians

No radiolarians could be extracted from the basal section, but the middle section yielded several exceptionally well preserved faunas (Figs 4, 8). Most of the productive samples can be assigned to Subzone 4 beta. This is confirmed by the co-occurrence of *Vallupus hopsoni* and *Perispyridium* near the base of the fertile sequence (LI 44). The overlying concretions lack Vallupinae (for paleoceanographic reasons) but contain *Perispyridium*, thus indicating Subzone 4 beta as well.

Near the top of the middle section, a well-preserved fauna (LI 35) contains *Vallupus hopsoni*, but lacks *Perispyridium*. This sample is, therefore, assigned to the base of Subzone 4 alpha.

No age diagnostic radiolarians could be extracted from the upper section.

Ammonites, belemnites and bivalves

First age diagnostic ammonites and belemnites from the Upper Jurassic sequence were listed by Tavera (1970) and Smellie *et al.* (1980). Smellie *et al.* (1980) found indication for Kimmeridgian (*Hibolites marwicki marwicki* Stevens and *Subplanites* sp.), early Tithonian (*Belemnopsis stoley* Stevens) and late Tithonian (*Berriasella* cf. *behrendseni* Burckhardt). Without referring to a

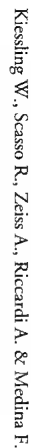


FIG. 8. — Occurrence of age diagnostic radiolarians discussed in the text. Only samples with good preservation and only taxa occurring in more than one sample are indicated. See text for single species occurrences.

section they gave a "balanced" age of early Tithonian for the "mudstone member".

Crame *et al.* (1993) found inoceramids of the *Retroceramus hausti* (Hochstetter) group near the base of the section suggesting (but not proving) Kimmeridgian. Near the top of their section Crame *et al.* (1993) found an ammonite-belemnite assemblage with Tithonian affinities. We could collect *Berriasella* and ? *Blanfordicerus* 25 m below the upper boundary of the exposed sequence providing evidence for late Tithonian. *Spiticeras* (*Spiticeras*) cf. *spitense* (Blanford) was found in the overlying President Beaches Formation. No ammonites were discovered in the radiolarian-rich interval.

In summary, the Anchorage Formation on Byers Peninsula ranges from Kimmeridgian/Tithonian to latest Tithonian. Radiolarians belonging to Subzone 4 beta are stratigraphically closer to what has been dated as Kimmeridgian than to the *Berriasella*-bearing late Tithonian/Berriasian (Fig. 4). The data support the conclusion that Subzone 4 beta should be completely assigned to the early Tithonian, although the evidence is less convincing than at Longing Gap.

LATE JURASSIC RADIOLARIAN BIOSTRATIGRAPHY

The biostratigraphic use of Late Jurassic radiolarians has only been recognized in the past twenty years starting with Pessagno (1977a). Since then a number of Late Jurassic radiolarian zonations have been proposed. There are basically four zonations in use for different regions of the world.

1. The North American zonation: this zonation dates back to the work of Pessagno (1977a). It was completely revised by Pessagno *et al.* (1984) and refined later by Pessagno *et al.* (1987b, 1993, 1994). The most recent update of the North American zonation was provided by Hull (1997). The chronostratigraphic calibration of radiolarian zones was established using ammonite, calpionellid and bivalve data.

2. The Tethyan zonation: a first zonation was presented by Baumgartner *et al.* (1980) based on unitary associations. This zonation was consid-

rably revised by Baumgartner (1984), chronostratigraphically updated by Baumgartner (1987), and reached its current state by the comprehensive contribution of Baumgartner *et al.* (1995a). The chronostratigraphic calibration of radiolarian zones was established by using ammonite, calpionellid and calcareous nannofossil ages.

3. The "Japanese" zonations: several Japanese scientists developed zonations which are mostly applied to western Pacific sections, but are also useful in the Tethys. The most widely used zonation has been developed by Matsuoka & Yao (1986) which was updated by Matsuoka (1992, 1995b). The chronostratigraphic calibration is partly provided by ammonite and calcareous nannofossil data, but mostly relies on correlation with dated Tethyan and North American radiolarian-bearing sequences.

4. The Russian zonations: zonations of the Caucasus Region and the Russian Far East were proposed by Tikhomirova (1988) and Vishnevskaya (1993). The Jurassic zones in the Caucasus are calibrated by ammonites and aptychi, whereas the Russian Pacific margin is poorly dated by *Buchia* sp. Late Jurassic radiolarian stratigraphy on the Russian platform is still in its infancy with only one preliminary zonation available (Kozlova 1994).

As explained above, we mostly applied the North American radiolarian zonation for dating our radiolarian samples. The primary, secondary and corporeal markers of Pessagno *et al.* (1993) that are present in Antarctica are listed in Table 1. The application of the new Unitary Association stratigraphy of Baumgartner *et al.* (1995a) is hampered by the scarcity of Tethyan taxa. However, there are several species that have been used in Tethyan zonations as well (Table 1). The occurrences of species discussed below are indicated in Figure 8, if they were traced in more than one sample. Species occurring in only one sample are:

- LI 31: *Acanthocircus furiosus* Jud;
- K 8-1: *Saitoum pagei* Pessagno;
- K 12: *Protunuma japonicus* Matsuoka & Yao;
- K 13: *Sethocapsa trachyostraca* Foreman;

TABLE 1. — Antarctic radiolarian taxa used in published zonations.

Radiolarian marker taxa used in the North American zonation (Pessagno <i>et al.</i> 1984, 1987b, 1993, 1994)	Radiolarian species used in the Tethyan zonation (Baumgartner <i>et al.</i> 1995a)
<i>Bivallupus</i>	<i>Acaeniotyle umbilicata</i> (Rüst) gr.
<i>Caneta hsui</i> (Pessagno)	<i>Acanthocircus furiosus</i> Jud
<i>Hsuum mclaughlini</i> Pessagno & Blome s.l.	<i>Acastea diaphorogona</i> (Foreman)
<i>Orbiculiforma lowreyensis</i> Pessagno	<i>Angulobracchia biordinalis</i> Ozvoldova
<i>Parvicingula blowi</i> Pessagno	<i>Tethysetta boesii</i> gr. (Parona)
<i>Parvicingula colemani</i> Pessagno & Blome	<i>Crucella theokaftensis</i> Baumgartner
<i>Parvicingula excelsa</i> Pessagno & Blome	<i>Emiluvia chica</i> Foreman
<i>Parvicingula jonesi</i> Pessagno	<i>Emiluvia hopsoni</i> Pessagno
<i>Praeparvicingula vera</i> (Pessagno & Whalen)	<i>Emiluvia pessagnoi</i> Foreman
<i>Perispyridium</i>	<i>Gongylothorax favosus</i> Dumitrica
<i>Tethysetta boesii</i> (Parona)	<i>Haliodictya</i> (?) <i>antiqua</i> s.l. (Rüst)
<i>Vallupus hopsoni</i> Pessagno & Blome	<i>Homoeoparonaella elegans</i> (Pessagno)
	<i>Hsuum</i> sp. aff. <i>H. questaense</i> Pessagno (= <i>Hsuum mclaughlini</i> s.l.)
	<i>Hsuum teliformis</i> Jud
	<i>Loopus primitivus</i> (Matsuoka & Yao)
	<i>Napora pyramidalis</i> Baumgartner
	<i>Perispyridium ordinatum</i> (Pessagno) gr.
	<i>Podobursa spinosa</i> s.l. (Ozvoldova)
	<i>Podocapsa amphitreptera</i> Foreman
	<i>Protunuma japonicus</i> Matsuoka & Yao
	<i>Saitouma pagei</i> Pessagno
	<i>Sethocapsa trachyostraca</i> Foreman
	<i>Suna schiodes</i> (Foreman) s.l.
	<i>Triactoma mexicana</i> Pessagno & Yang
	<i>Triactoma tithonianum</i> Rüst
	<i>Tritrabs rhododactylus</i> Baumgartner
	<i>Zhamoidellum ventricosum</i> Dumitrica

- K 14-1: *Haliodictya* (?) *antiqua* (Rüst) s.l.;
- K 23: *Orbiculiforma lowreyensis* Pessagno;
- K 27: *Podobursa spinosa* (Ozvoldova) s.l.

We first discuss the value of the North American zonation and subsequently try to link our data to the zonation of Baumgartner *et al.* (1995a) and Matsuoka (1995b). The Russian zonations are not discussed, since their stratigraphic resolution is either too coarse or they consider poorly defined species.

THE NORTH AMERICAN RADIOLARIAN ZONATION
The major pitfall of the North American zonation is the reference to species absence in stratigraphic assignment. As zonal boundaries are defined by first or last occurrences of marker taxa, the reliability of their absence has to be cri-

tically evaluated for each section or sample. This can be achieved by observing the quantitative distribution of marker taxa within their range and by judging the possibility that species absence is merely a result of oceanographic, diagenetic or stochastic bias.

As discussed above, we can recognize the North American Zones 3 and 4, and probably zone 5 in Antarctica. Zone 3 was originally assigned to the early Tithonian, but it has been demonstrated by Baumgartner *et al.* (1995a) that its base may reach down to the middle Oxfordian.

The base of Zone 4 was originally (Pessagno *et al.* 1984, 1987) calibrated by corresponding closely to the first occurrence of *Crassicollaria intermedia* (Durand Delga) and late Tithonian ammonites in Mexico and by occurring below the *Buchia piochii* zone of Jones *et al.* (1969) in California.

TABLE 2. — Summary of modifications in the chronostratigraphic assignment of North American radiolarian zones resulting from our new data.

	Pessagno <i>et al.</i> (1977a, b, 1984, 1987, 1993)	This paper
Base of Zone 5	Tithonian/Berriasian boundary	Tithonian/Berriasian boundary?
Base of Subzone 4 alpha	early late/late late Tithonian boundary	Early Tithonian (Darwini zone)
Base of Zone 4	early/late Tithonian boundary	Kimmeridgian/Tithonian boundary

It was thus correlated with the early Tithonian/late Tithonian (*sensu* Gallico) boundary. Recently, this boundary was lowered to the late early Tithonian (Pessagno pers. comm. 1997; Hull 1997).

The new results from the Antarctic sections demand a revision of the chronostratigraphic calibration for the base of Zone 4 and the base of Subzone 4 alpha given by Pessagno *et al.* (1993). Before we do so, we have to check the reliability of our radiolarian ages, especially referring to the marker taxa of Pessagno *et al.* (1993).

The base of Zone 4 was originally (Pessagno *et al.* 1984) defined by the first occurrence of *Acanthocircus dicranacanthos* and *Vallupus hopsoni*. Since *A. dicranacanthos* is absent in Antarctica, due to the high paleolatitude, the first occurrence of the pantanelliid *Vallupus hopsoni* (Fig. 5I) is crucial in our discussion. The Austral character of the radiolarians requires caution in the interpretation of the first occurrence date of this species. Since the abundance (or probability of detection) of the pantanelliid subfamily Vallupinae is correlated with the overall abundance of Pantanelliidae, it is very unlikely to detect *Vallupus hopsoni* in standard residues (about 1 g in the Antarctic material), if pantanelliids make up less than 5% of a radiolarian sample. This fact may be partly responsible for the erroneous correlation of Pessagno *et al.* (1993). The abundance and diversity of pantanelliids was thought to decrease rapidly with latitude in the paleolatitudinal model of Pessagno & Blome (1986). Although pantanelliids sum up to 50.1% in one sample from Longing Gap, their abundance is strongly fluctuating in Antarctica. In Longing Gap (Fig. 3) the first occurrence of *Vallupus hopsoni* is noted in a sample (K 20-1) with 12.1% total pantanelliid abundance. The

samples taken from just 2 and 3 m below (K 18, 19) contain a rich radiolarian fauna, but yield few pantanelliids. Only the samples K 14-1 and K 15 provide firm evidence for an age older than Subzone 4 beta. They contain diverse and abundant pantanelliids (15.6 and 13.8%, respectively) and even some vallupins, but no *Vallupus* was detected. Our last firm ammonite evidence for the Kimmeridgian is from between K 15 and K 18, but our first evidence of Tithonian stems from the level of K 18. Thus the first appearance of *Vallupus hopsoni* is only reliable within a 40 m thick interval separating K 15 and K 20-1. Although we do have ammonite evidence for early Tithonian below K 20-1 (*Hybonotum* zone), we cannot reject a late Kimmeridgian age for the base of Zone 4.

The last occurrence of *V. hopsoni* has been used as a correlative marker within Subzone 4 alpha. At Longing Gap concretion level K 33/34 is the last horizon containing this species. This horizon is dated as middle/late Tithonian and is probably equivalent to the *Windhausenicerias internispinosum* zone of Argentina. Although we are not able to provide firm evidence for this zone in Antarctica (see discussion above), the presence of *V. hopsoni* in the *W. internispinosum* zone was established by Pujana (1991, 1996) in Argentina. In the Southern Alps, Subzone 4 alpha with *V. hopsoni* was recorded in the late middle to earliest late Tithonian *Chitinoidea* zone (cf. Kiessling 1995).

Perispyridium (Fig. 5J) is the only other primary marker taxon in Zone 4 that is present in Antarctica. Its last occurrence marks the top of Subzone 4 beta. The last occurrence of this genus provides a reliable datum, since *Perispyridium* is common throughout its stratigraphic range (with two exceptions) and suddenly disappears in the

				Primary Marker Taxa	Secondary and Corporeal Marker Taxa
BERR.	early	Zone 5	Subzone 5A	<i>Parvicingula jonesi</i>	
	late		Subzone 4α	<i>Ristola altissima</i> ↑ <i>Ristola procera</i> ↑	<i>Parvicingula colemani</i> ↑ <i>Parvicingula excelsa</i> ↑ <i>Hsuum mclaughlini</i> ↑ <i>Orbiculif. lowreyensis</i> ↑
TITHONIAN	early	Zone 4	Subzone 4β	<i>Vallupus hopsoni</i> ↓ <i>Perispyridium</i> ↑ <i>Acanthoc. dicranacanthos</i> ↓	<i>Parvicing. jonesi</i> ↓ <i>P. colemani</i> ↓
	late		Subzone 3α	<i>Napora burckhardti</i> ↑	
KIMMERIDGIAN	early	Zone 3		<i>Mirifusus guadalupensis</i> ↑	<i>Hsuum maxwelli</i> ↑ <i>Turanta</i> ↑
	late		Subzone 3β	<i>Mirifusus baileyi</i> ↓	
OXFORDIAN	middle	Zone 2	Subzone 2α1	<i>Loopus</i> ↓	
	early		Subzone 2α2	<i>Parvicingula s.s.</i> ↓	

FIG. 9. — New chronostratigraphic assignment of the radiolarian biostratigraphy of Pessagno (1977b), Pessagno *et al.* (1984, 1987, 1993, 1994, 1996). Our data allow a modification of the Zone 3/Zone 4 boundary and the boundary between Subzone 4 alpha and 4 beta. The lower zones were modified following Baumgartner *et al.* (1995a, fig. 13). Marker taxa that are present in Antarctica are printed in bold. In this figure we use the Tithonian *sensu* Gallico as do Pessagno *et al.*; however it should be noted that subzone 4 beta ends before the middle Tithonian *sensu* Gerth.

sequence. However, there is a relatively thick interval with only sparse radiolarian faunas above the last record of *Perispyridium* in K 29. The first radiolarian sample with a sure absence of this genus is K 30b, which is only a few meters below the first record of the latest early Tithonian (*sensu* Gerth) *Mendozanus* zone. Hence, the top of Subzone 4 beta is assigned to the late early Tithonian (*sensu* Gerth = early early Tithonian *sensu* Gallico).

According to Pessagno *et al.* (1987), the last occurrence of *Parvicingula colemani* is noted in the upper part of Subzone 4 alpha (corporeal marker taxon). In Longing Gap, the last samples with *P. colemani* s.l. are above the level with first

evidence of berriasellid ammonites indicating late Tithonian. Above the last occurrence of *P. colemani* no primary marker taxa (with the exception of *Parvicingula jonesi* Pessagno) of the North American zonation are present. However, Hull (1997) used the last occurrence of *Hsuum mclaughlini* as a secondary marker to define the top of Zone 4. This species is present near the top of the Longing Gap Section (K 65) which is assigned to the Berriasian. This would indicate that the top of Zone 4 should be assigned to the early Berriasian, consistent with new results of Pessagno *et al.* (1996). However, a relatively great faunal change is noted in Antarctica from K 60 onward, approximately consistent with the

Jurassic-Cretaceous boundary. Since no primary marker taxa are present, we tentatively correlate the Zone 4-Zone 5 boundary with the Jurassic-Cretaceous boundary and the first occurrence of *Williriedellum ruesti* (Tan Sin Hok) as figured in Kiessling & Scasso (1996, pl. 2/14).

Considering the statements above, we can revise the chronostratigraphic assignments of the North American radiolarian zonation (Table 2, Fig. 9). We are currently not able to affirm what led to the erroneous chronostratigraphic assignment of the zones and subzones discussed above. They may partly be due to the complex tectonic settings of both Mexico and California.

EVIDENCE FROM OTHER AREAS

The new chronostratigraphic assignment of the Zone 3-Zone 4 boundary is supported by new data from Germany.

Recent investigations in the Upper Jurassic of Southern Germany produced a very well-preserved and diverse radiolarian fauna in the Mörsheim Formation (Zügel 1997) including *V. hopsoni*. The Mörsheim Formation is correlated with the upper part of the *Hybonoticeras hybonotum* zone (Zeiss 1977) equivalent to an early early Tithonian age. In his ongoing work, Zügel (pers. comm. 1997) could recover *V. hopsoni* also in the chert-bearing limestones of Schamhaupten (Bavaria, Southern Germany). The locality is currently assigned to the uppermost Kimmeridgian (Bausch 1963).

In summary, the data from Germany do support an older age for the Zone 3-Zone 4 boundary. We can thus conclude that *V. hopsoni* first appears very close to the Kimmeridgian/Tithonian boundary. Other reports (Matsuoka 1992, Chiari *et al.* 1997) on the first occurrence of *V. hopsoni* do also support this interpretation, although they are not directly correlated with ammonite data.

ZONATION OF BAUMGARTNER *ET AL.* (1995B)

We have discussed above that the applicability of the Tethyan unitary association zonation (UAZ) is restricted owing to biogeographic differences. Additionally, there is a general trend from assemblages containing Tethyan taxa at the base to

assemblages with a high degree of endemism at the top in the Ameghino Formation. However, a limited comparison is possible, if we sum up all our samples from the zones and subzones of the North American zonation. Three of the new unitary associations of Baumgartner *et al.* (1995a) were expected to occur in Antarctica:

- UAZ 11: late Kimmeridgian-early Tithonian;
- UAZ 12: early-early late Tithonian;
- UAZ 13: latest Tithonian-earliest Berriasian.

We will show below that UAZ 10 is unexpectedly also present at Longing Gap.

At Longing Gap, our samples from Zone 3, Subzone 3 alpha (K 2-K 15) contain the Tethyan taxa *Acaeniotyle umbilicata* gr. (Fig. 5L), *Acastea diaphorogona*, *Angulobracchia biordinalis*, *Archaeodictyon mitra miaoensis*, *Crucella thekaensis* (Fig. 5F), *Gongylorhynchus favosus* (Fig. 5N), *Haliodictya (?) antiqua* s.l. (Fig. 5K), *Hsuum* sp. aff. *H. cuestaense*, *Napora pyramidalis*, *Perispyridium ordinarium* gr. (Fig. 5J), *Protunuma japonicus*, *Saitoum pagei*, *Sethocapsa trachystrata* (Fig. 5M), *Triactoma mexicana*, and *Zhamuiddellum ventricosum*. This assemblage was not observed in the Tethys and trying to apply the UAZ 95 leads to contradictory results. *Triactoma mexicana* (samples K 8-1, K 13) is predicted to range not higher than UAZ 9, but *Acaeniotyle umbilicata* (samples K 6, K 12, K 13, K 14-1) is not supposed to occur before UAZ 10. It is likely that the total range of *T. mexicana* is poorly defined in the UAZ considering the zonal assignment of *T. mexicana* to Subzone 4 beta by Pessagno *et al.* (1989) and its occurrence in UAZ 12 in the Southern Alps (cf. Kiessling 1995). *Gongylorhynchus favosus* is not reported above UAZ 10 according to Baumgartner *et al.* (1995a). This species was found only at the very base of the section (K 2, K 4) which may actually be assigned to UAZ 10. The samples above K 4 are assigned to UAZ 10-11. There are not sufficient Tethyan radiolarians to precisely define the UAZ of Baumgartner *et al.* (1995a). However, the application of the unpublished 127 UA range chart on the lumped zone 3 fauna results in a firm correlation with UAZ 10 (Guex, pers. comm. 1998). *Triactoma mexicana* ranges up to UAZ 11 in this recomputing.

Within Subzone 4 beta the following taxa used by Baumgartner *et al.* (1995a) are present in Antarctica: *Acanthocircus furiosus* (Fig. 5H), *Acastea diaphorogona*, *Angulobracchia biordinalis*, *Emiluvia chica*, *Emiluvia pessagnoii* s.l., *Gorgansium* sp., *Homoeoparonaella elegans*, *Hsuum* aff. *cuestaense*, *Hsuum feliformis* (only detected in James Ross Island), *Loopus primitivus* (Fig. 5B), *Napora pyramidalis*, *Perispyridium ordinarium* gr., *Podobursa spinosa* s.l., *Podocapsa amphitrepta* s.l., *Suna echiodes* s.l. (Fig. 5O), *Triactoma tithonianum*, *Tritrabs rhododactylus* (Fig. 5G).

Again, there are some contradictions applying the unitary association zonation. *Gorgansium* ranges from UAZ 3-8 according to Baumgartner *et al.* (1995a), whereas *Hsuum feliformis* is thought to occur not earlier than UAZ 13. Leaving aside these problematic taxa would result in a correlation with UAZ 10 for the assemblage, as defined by *A. furiosus* (UAZ 10-20) and *H. elegans* (UAZ 4-10). However, *H. elegans* only occurs up to the middle part of Subzone 4 beta at Longing Gap. Above the last occurrence of *H. elegans* the assemblage would be assigned to UAZ 10-11. Again, the application of the 127 UA range chart helps to define the correlation more precisely. Guex (1998, pers. comm.) states that the lumped Subzone 4 beta fauna perfectly correlates with UAZ 11.

Only a few Tethyan taxa were found in the assemblages assigned to Subzone 4 alpha and Zone 5: *Gorgansium* sp., *Hsuum* aff. *cuestaense*, *Tethysetta boesii* gr. (Fig. 5C), *Triactoma tithonianum* are present indicating UAZ 10-13. A more exact correlation is not possible. Thus the presence of UAZ 12-13 cannot be proved in Antarctica.

The stratigraphic correlation of the North American zones with the UAZ can be controlled by new data from Europe (Kiessling 1995; Chiari *et al.* 1997; Zügel 1997). *V. hopsoni* was reported from UAZ 10 (Chiari *et al.* 1997) to UAZ 12-13 (Zügel 1997, cf. Kiessling 1995, 1996). Two samples from the Southern Alps bear *V. hopsoni* and lack *Perispyridium* and can thus be assigned to the base of Subzone 4 alpha. The

sample from Ponte Setra near Fonzasco (see Kiessling 1996 for locality description) is from the transitional interval between the Ammonitico Rosso Superiore and the Maiolica which has been assigned to the late middle to earliest late Tithonian *Chitinnidella* zone by Grandesso (1977). This sample (PS 13) contains many species that make their first occurrence in UAZ 13: *Emiluvia chica decussata* Steiger, *Obesacapsula ruscoensis umbriensis* Jud, *Paronaella* (?) *tubulata* Steiger, *Pyramispongia barnsteinensis* (Steiger), and *Syringocapsa amphorella* (Jud). On the other hand, species like *Syringocapsa spinellifera* Baumgartner and *Willriedellum crystallinum* Dumitrica are also present. These have their last occurrence in UAZ 12 and UAZ 11, respectively. Therefore, PS 13 is preliminarily assigned to UAZ 12.

In summary the total range of *V. hopsoni* is from UAZ 10 to at least UAZ 12. The related form *Vallupus japonicus* has been shown by Matsuoka (1998) to range up to the early Berriasian (UAZ 13). UAZ 10 radiolite assemblages can be observed from the base of the Longing Gap Section (Kimmeridgian) up to a horizon that has been dated as early Tithonian by ammonites. Baumgartner *et al.* (1995a) indicated a late Oxfordian-early Kimmeridgian age for UAZ 10. Although Baumgartner *et al.* (1995a: 1033) provide good evidence for this age, the age of the succeeding UAZ 11 is much less well defined. Considering the results above, we can conclude that UAZ 10 ranges up to at least the latest Kimmeridgian *Beckeri* zone. The new correlation of UAZ 10-13 with the North American zonation and their chronostratigraphic assignment are indicated in Figure 10.

ZONATION OF MATSUOKA (1995B)

The comparison with Matsuoka (1995b) is hampered by the rather coarse stratigraphic resolution of Matsuoka's Late Jurassic zonation. Only the *Pseudodictyonitza primitiva* zone can be traced in Antarctica, owing to the absence of other age-diagnostic taxa. This interval zone is defined by the last occurrence of *Hsuum maxwelli* at its base and the first occurrence of *Pseudodictyonitza carpatica* (Lozynyak) at its top. It is supposed to range from the early to the middle Tithonian.

	NORTH AMERICAN ZONES	TETHYAN ZONES (UAZ 95)	
BERRIASIAN	5	13	
TITHONIAN	late 4 α	12	Range of <i>Vallupus hopsoni</i>
	early 4 β	11	
KIMMERIDGIAN	3 α	10	

FIG. 10. — Correlation of the North American (Pessagno *et al.* 1993) and Tethyan (Baumgartner *et al.* 1995a) zonations for the Kimmeridgian/Tithonian interval.

According to Matsuoka (1995a, fig. 3), the *P. primitiva* zone ranges from the base of Zone 3 to the top of Subzone 4 beta. Considering our results and the correlation chart of Baumgartner *et al.* (1995a, fig. 13) this would imply a total range of the *P. primitiva* zone from the middle Oxfordian to early Tithonian. However, as the last occurrence of *Hsuum maxwelli* is noted within upper Subzone 3 alpha according to Pessagno *et al.* (1993), we suggest that the *Pseudodictyonitza primitiva* zone starts in the late Kimmeridgian. Since *Pseudodictyonitza carpatica* is absent due to biogeographical differences, the top of the *Pseudodictyonitza primitiva* zone cannot be defined.

Although the total range of *Loopus primitivus* (= *Pseudodictyonitza primitiva*) is uncertain according to Matsuoka (1995b) its major occurrence is definitely within the *Pseudodictyonitza primitiva* zone. At Longing Gap and Livingston Island, *L. primitivus* is found in Subzone 4 beta and at the very base of Subzone 4 alpha. Its first occurrence coincides with the first occurrence of *V. hopsoni* and its last occurrence is noted slightly above the last occurrence of *Perispyridium*. This agrees with a latest Kimmeridgian to probably middle Tithonian age and is consistent with Matsuoka's chronostratigraphic assignment for the *Pseudodictyonitza primitiva* zone.

CONCLUSIONS

New paleontological data from two Upper Jurassic localities on the Antarctic Peninsula allow the elaboration of a combined ammonite and radiolarian stratigraphy, provide a high stratigraphic resolution and allow to revise current chronostratigraphic calibrations of radiolarian zones.

The Ameghino Formation at Longing Gap ranges from the Kimmeridgian to the early Berriasian, whereas the Anchorage Formation at Byers Peninsula ranges from the Kimmeridgian/Tithonian to the latest Tithonian. Zone 3, Subzone 3 alpha, Zone 4, Subzones 4 beta and 4 alpha and probably the base of Zone 5 could be traced at Longing Gap, whereas on Byers Peninsula only Subzone 4 beta assemblages are well established.

The chronostratigraphic calibration of Zone 4 and its subzones as used in the North American radiolarian zonation (Pessagno *et al.* 1993) is revised herein. The base of Zone 4 is assigned to the Kimmeridgian/Tithonian boundary interval and the base of Subzone 4 alpha is located within the early Tithonian.

The North American radiolarian zones can be correlated with the unitary association zonation (Baumgartner *et al.* 1995a). Uppermost Zone 3, Subzone 3 alpha correlates with UAZ 10 and the base of Zone 4 agrees with UAZ 11 in Antarctica. Higher up in the sequences no correlation with the UAZ 95 is possible owing to increasing biogeographical differences. Evidence from the Southern Alps suggests that *Vallupus hopsoni* ranges up to at least UAZ 12.

The interval zonation used by Pessagno *et al.* (1993) has the advantages to be applicable to tropical as well as high latitude settings and to rely on only a few age diagnostic radiolarians. However, the absence of marker taxa has to be carefully proved, in order to overcome preservational, paleoceanographic and stochastic biases. With the chronostratigraphic corrections in this paper and those of Baumgartner *et al.* (1995a), we hope that the North American zonation can now be applied everywhere without contradictions. A major task for the future will be the definition of the Zone 4-Zone 5 boundary with the aid of high latitude radiolarians.

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